# Complementary observational constraints on climate sensitivity

Nathan M. Urban

Klaus Keller

Department of Geosciences, Penn State, University Park, Pennsylvania, USA

A persistent feature of empirical climate sensitivity estimates is their heavy tailed probability distribution indicating a sizeable probability of high sensitivities. Previous studies make general claims that this upper heavy tail is an unavoidable feature of (i) the Earth system, or of (ii) limitations in our observational capabilities.

Here we show that reducing the uncertainty about (i) oceanic heat uptake and (ii) aerosol climate forcing can — in principle — cut off this heavy upper tail of climate sensitivity estimates. Observations of oceanic heat uptake result in a negatively correlated joint likelihood function of climate sensitivity and ocean vertical diffusivity. This correlation is opposite to the positive correlation resulting from observations of surface air temperatures. As a result, the two observational constraints can rule out complementary regions in the climate sensitivity-vertical diffusivity space, and cut off the heavy upper tail of the marginal climate sensitivity estimate.

## 1. Introduction

Most current observational estimates of climate sensitivity (the projected equilibrium temperature change for a doubling of carbon dioxide concentration) produce positively skewed probability density functions (pdfs) [*Meehl et al.*, 2007; *Knutti and Hegerl*, 2008]. This form of pdf implies that rather high climate sensitivity values (e.g., above 9 K) still have a sizeable probability. Whether the true climate sensitivity is indeed located in this "heavy upper tail" [*Forest et al.*, 2002; *Tol and de Vos*, 1998; *Royer et al.*, 2007] of current estimates is a question of considerable policy relevance [*Keller et al.*, 2004; *Weitzman*, 2007]. This is because the projected climate change impacts typically rise in a highly nonlinear function with the climate sensitivity [*Yohe et al.*, 2004; *Nordhaus*, 2008].

The uncertainty in climate sensitivity arises primarily from uncertainty in the dynamical feedbacks which act on external radiative forcing, such as water vapor, ice albedo, and cloud feedbacks [*Bony et al.*, 2006]. Estimates based on surface temperature alone are confounded by the uncertain transient response due to oceanic thermal inertia [*Hansen et al.*, 1985]. Several studies have shown how combining different types of observational constraints (e.g., global surface temperature and ocean heat time series) can reduce the uncertainty about the climate sensitivity [*Forest et al.*, 2002; *Knutti et al.*, 2002; *Gregory et al.*, 2002]. The inclusion of more observations is generally expected to reduce uncertainty, but as we will discuss, surface temperature and ocean heat in particular are complementary to each other when estimating the uncertainty in climate sensitivity.


0094-8276/09/2008GL036457$5.00

*Roe and Baker* [2007] claims that the heavy tail of climate sensitivity is "an inevitable and general consequence of the nature of the climate system". The logic behind this reasoning is that a combination of many uncertain feedback factors approaches, via the central limit theorem, a normally distributed total feedback factor. This normally distributed prior for the feedback results in, via the nonlinear relationship between feedback and climate sensitivity, a heavy upper tail of climate sensitivity estimates. However, this reasoning neglects the additional constraint on the total feedback provided by observations of the overall system response. *Allen et al.* [2006] reviews the problem from an observational perspective, citing uncertainties in the observed forcing and energy imbalance as limiting factors, and concludes that high values of equilibrium warming "are not and, for many data sources, cannot be excluded by the comparison of models with observations".

Here we analyze (i) the mechanisms causing the heavy upper tail and (ii) how observations could test whether the climate sensitivity is indeed located in this region. We show that combining high precision ocean heat observations with surface temperature can — in principle — cut off the heavy tail of climate sensitivity estimates. This is because the two constraints produce a joint likelihood function of climate sensitivity and vertical diffusivity which is mutually exclusive of either very low or very high climate sensitivity estimates. In a nutshell, a tail of the climate sensitivity estimate which is allowed by one observational constraint is excluded by the other constraint.

## 2. Methodology

We use perfect model experiments to demonstrate that the heavy tail of climate sensitivity estimates depends on the nature and quality of the considered observational constraints. We perform two experiments. In a first experiment, we map the relationship between the transient warming (which is the observational constraint) and the equilibrium climate sensitivity (which is the inferred parameter). Specifically, we calculate the response of surface temperature and ocean heat anomalies as a function of climate sensitivity, using a range of assumptions about vertical ocean diffusivity. In a second experiment, we perform a perfect model assimilation to estimate the climate sensitivity from hypothetical observations of changes in surface air temperatures and oceanic heat anomalies. Following *Forest et al.* [2006], we consider uncertainty in the climate sensitivity and vertical diffusivity. To demonstrate our general point about the effect of parameter correlations on the heavy upper tail of climate sensitivity, we neglect uncertainty in aerosol forcing. We return to this assumption in the Discussion section.

Using the DOECLIM climate model [*Kriegler*, 2005; *Tanaka et al.*, 2007], a zero dimensional energy balance model coupled to a one dimensional diffusive ocean, we calculate the global surface temperature anomaly and ocean heat anomaly using historical forcings from 1750 to 2000 [*Tanaka et al.*, 2007]. We assume a climate sensitivity of 3.26 K and a vertical diffusivity of 0.55 cm$^2$ s$^{-1}$, obtained by the fit to observational data reported in *Kriegler* [2005]. We consider a surface temperature observation to be the year 2000 temperature relative to the 1961–1990 average, and an ocean heat observation to be the 1957–1996 global aggregate oceanic heat uptake.

To simulate observational error we superimpose Gaussian noise with standard deviations 0.05 K and $4 \times 10^{22}$ J, respectively. (For visual clarity, we do not superimpose this noise in Figure 2, so that the simulated observations are the model predictions and the joint likelihood is centered on the assumed parameter values. Assimilation experiments with different noise realizations indicate that our conclusions are robust to observational errors.) We calculate the likelihood of the simulated observations over a regular grid of climate sensitivities and vertical diffusivities. The observation errors of the two considered quantities are assumed to be independent, so their joint likelihood is the product of their individual likelihoods.

To obtain the joint posterior probability density of the estimated parameters, we multiply the joint likelihood by priors uniform between 0 and 10 K for climate sensitivity and between 0 and 4 cm$^2$ s$^{-1}$ for vertical diffusivity, and normalize the probability density function. The prior parameter ranges are chosen to be compatible with the ranges found in more realistic assimilation experiments [*Urban and Keller*, 2008]. A direct comparison of the diffusivity parameter range to field observations of ocean diffusivity, or to the diffusivity in more complex ocean models, is difficult due to the simplicity of our model. Integrating the joint posterior over vertical diffusivity gives the marginal posterior probability density of climate sensitivity.

## 3. Analysis

From an observational perspective, the heavy tail of climate sensitivity arises because of nonlinearity between the transient and equilibrium temperature responses (Fig. 1) [cf. *Hansen et al.*, 1985, which makes this point for the surface temperature constraint]. The transient response is what is observed, while the equilibrium response is what is estimated. If the two are nonlinearly related, a Gaussian uncertainty in the observed response produces a non-Gaussian uncertainty in the implied equilibrium climate sensitivity. The heavy upper tail of the climate sensitivity pdf appears because a small increase in the transient response corresponds to a large increase in the inferred climate sensitivity. A small error in measurement is thereby amplified into a large uncertainty in estimated sensitivity.

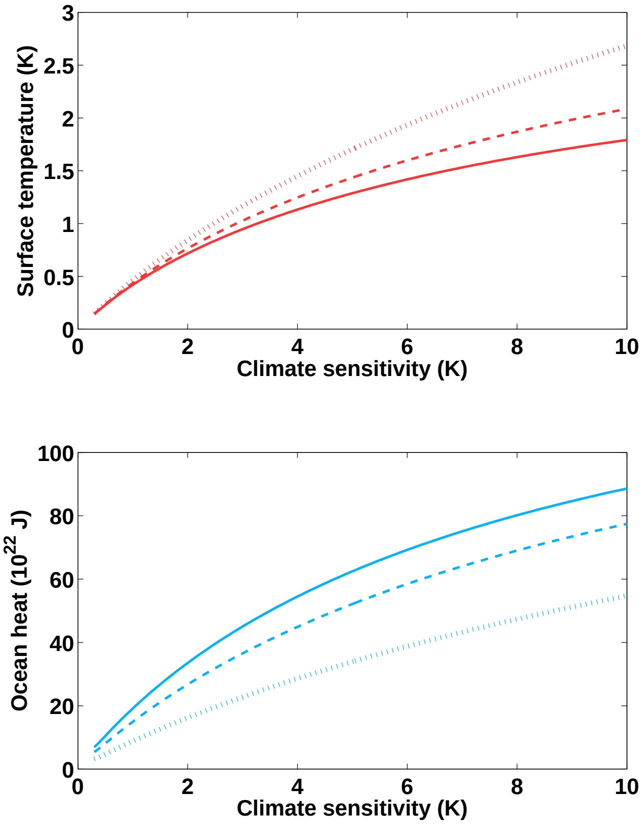


**Figure 1.** Transient climate response as a function of climate sensitivity, at fixed vertical ocean diffusivities $K_V = 0.1$ (dotted), 0.5 (dashed), and 1 cm$^2$ s$^{-1}$ (solid). *Upper:* Global mean surface temperature anomaly in the year 2000. *Lower:* Global ocean heat anomaly (1957–1996). Note that the response has negative curvature for either type of observation, but that surface temperature and ocean heat have opposite responses to changes in diffusivity.

The nonlinearity between observations and climate sensitivity occurs for both surface temperature and ocean heat observations (note the negative curvature of all curves in Fig. 1), leading to a heavy upper tail in the climate sensitivity pdf for either type of observation considered alone (Fig. 2, panel D, red and blue curves). A possibly surprising conclusion, however, is that these two heavy-tailed distributions can combine to produce a climate sensitivity pdf without the heavy tail (panel D, black curve). The resolution of this paradox lies in the fact that uncertainty in climate sensitivity is also influenced by the uncertain rate of ocean heat uptake, and that surface temperature and ocean heat observations rule out complementary regions of the sensitivity-diffusivity parameter space.

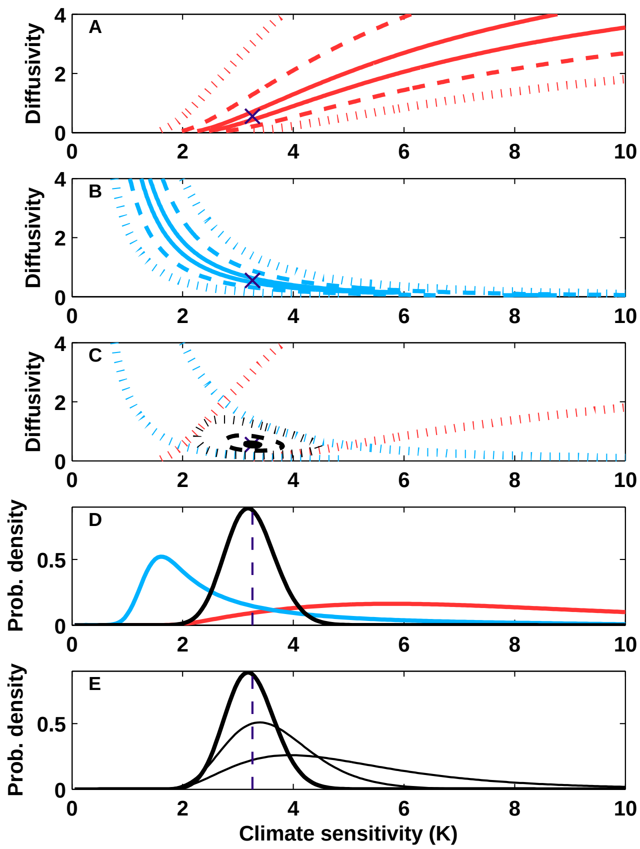


**Figure 2.** *Panels A, B, and C:* Joint likelihood functions for climate sensitivity (CS) and vertical ocean diffusivity ($K_V$). The likelihood in panel A assumes a hypothetical observation of the global mean surface temperature anomaly in the year 2000 (SAT). The likelihood in panel B assumes a hypothetical observation of global oceanic heat anomaly from 1957–1996 ($\Delta H$). Panel C assumes both observations, with likelihoods from A and B superimposed for reference. The solid, dashed, and dotted lines are 5, 50, and 95 % of the maximum likelihood (occurring at the true parameter values, crosses). *Panel D:* The marginal likelihood for climate sensitivity assuming both observations. The blue, red, and black lines are for $\Delta H$, SAT, and the combined $\Delta H$ and SAT observations, respectively. The dashed vertical line shows the true CS value. *Panel E:* The marginal likelihood for climate sensitivity due to increasing $\Delta H$ observation errors from 4 (thick curve), 12, to $24 \times 10^{22}$ J (thin curves).

Observations of changes in surface air temperatures result in positively correlated estimates of climate sensitivity and ocean diffusivity (Fig. 2, panel A). This is because the climate sensitivity signal in the observed warming is confounded by the amount of warming "in the pipeline" due to the lagged response of the oceans [*Hansen et al.*, 1985, 1997]. A given surface air temperature change is consistent with either a relatively large heating which is penetrating rapidly into the oceans and delaying some of the surface warming (i.e., a high climate sensitivity and a high ocean diffusivity), or a relatively small heating which is penetrating slowly into the oceans so the surface warming is quickly experienced (i.e., a low climate sensitivity and a low ocean diffusivity). This relation can also be seen in the upper panel of Fig. 1, where for a fixed transient response, larger diffusivities correspond to larger sensitivities.

In contrast, observations of changes in oceanic heat content result in negatively correlated estimates of climate sensitivity and ocean diffusivity (panel B). This is because a given change in oceanic heat content is consistent with either a relatively large heating which is penetrating slowly into the oceans (i.e., a high climate sensitivity and a low ocean diffusivity) or a relatively small heating which is penetrating rapidly into the oceans (i.e., a low climate sensitivity and a high ocean diffusivity). This can also be seen in the lower panel of Fig. 1, where for a fixed transient response, larger diffusivities correspond to smaller sensitivities.

Considered separately, the information contained in (i) the changes in surface air temperatures and (ii) the changes in oceanic heat content result in right skewed estimates of climate sensitivity (panel D, red and blue lines, respectively). However, combining these two lines of evidence results in an approximately symmetric pdf for the climate sensitivity (panel D, black line). Combining the information contained in atmospheric and oceanic observations can hence, in principle, cut off the heavy upper tail of climate sensitivity estimates. This effect is due to the interactions between the two constraints. Specifically, high climate sensitivity estimates that would be consistent with the surface air temperature constraint (panel A) are inconsistent with the oceanic heat constraint (panel B). Likewise, low climate sensitivity estimates that would be consistent with the oceanic heat constraint (panel B) are inconsistent with the surface air temperature constraint (panel A). The joint posterior for the combined observations lies in the mutually consistent region where the posteriors for each individual observation overlap (panel C, black curves).

## 4. Discussion

The heavy upper tail of climate sensitivity can be reduced when both observational constraints are combined. This tail thinning occurs because the high sensitivities allowed by the temperature constraint are disfavored by the ocean heat constraint, and vice versa. Surface temperature observations permit high climate sensitivities if there is substantial unrealized "warming in the pipeline" from the oceans. However, complementary ocean heat observations can be used to test this and can potentially rule out large ocean warming. Ocean heat observations are compatible with high sensitivities if there is substantial surface warming which is penetrating poorly into the oceans. Again, complementary surface temperature observations can test this, and can potentially rule out large surface warming. High climate sensitivities can thus be excluded when both observational constraints are jointly applied. In parameter space, these complementary constraints take the form of (i) a positive correlation between climate sensitivity and ocean vertical diffusivity implied by surface temperature observations, and (ii) an opposite, negative correlation implied by ocean heat observations (Fig. 1; Fig. 2, panels A & B).

## 5. Caveats

It is important to stress that our simple analysis neglects several likely important processes and sources of uncertainty. For example, our analysis neglects uncertainties about historic climate forcings [*Forest et al.*, 2002]. Since direct and indirect aerosol forcings are significant and their combined uncertainty is comparable in size to the forcing itself [*Alley et al.*, 2007], treatment of this uncertainty will widen the tails of the climate sensitivity pdf [*Allen et al.*, 2006]. The specific conclusions shown in Figs. 1 and 2 are hence contingent on (i) the chosen model structure and (ii) a case where the forcing uncertainty has been reduced to negligible levels. The analysis outlined here cannot exclude large climate sensitivities arising from slow system feedbacks not represented in our simple model, such as ice sheet or carbon cycle feedbacks [*Hansen et al.*, 2008]. Decades of additional observations may be required to substantially reduce the uncertainties in slow feedbacks, the climate response time, and the total radiative forcing. Future research with more realistic models (e.g., *Weaver et al.* [2001]) and considering forcing uncertainty (cf. *Forest et al.* [2002]) is needed to translate our general findings into specific recommendations for the design of observation systems.

## 6. Conclusions

The observational constraints considered in published studies [*Meehl et al.*, 2007] provide little guidance to decide the question whether the real climate sensitivity is indeed located in the heavy upper tail. In our analysis, cutting off the heavy tail required (i) neglecting model structural uncertainty, (ii) a reduction of the aerosol forcing uncertainty to negligible levels, and (iii) reduced uncertainty in oceanic heat uptake. Our analysis suggests that one promising avenue to decide whether the true climate sensitivity is indeed located in the heavy upper tail of current estimates is through improving the skill of the existing ocean observation system to estimate the anthropogenic heat uptake [*AchutaRao et al.*, 2006; *Levitus et al.*, 2005]. The skewness of the climate sensitivity estimate in our analysis hinges critically on the observation error of the oceanic heat content observations: reducing the uncertainty about the oceanic heat uptake shortens the upper tail of the resulting climate sensitivity estimates (Fig. 2, panel E).

## 7. Acknowledgments

We thank Elmar Kriegler for providing the source code of his model and for fruitful discussions. We also thank the anonymous reviewers whose insightful comments clarified this manuscript. Funding for this project was provided by the National Science Foundation and by the U.S. Environmental Protection Agency (under Purchase Order EP07H000339). Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding entity.

## References

AchutaRao, K. M., B. D. Santer, P. J. Gleckler, K. E. Taylor, D. W. Pierce, T. P. Barnett, and T. M. L. Wigley, Variability of ocean heat uptake: Reconciling observations and models, *Journal of Geophysical Research-Oceans*, *111*, C05,019, 2006.

Allen, M., et al., Observational constraints on climate sensitivity, in *Avoiding Dangerous Climate Change*, edited by H. J. Schnellnhuber, W. Cramer, N. Nakicenovic, T. Wigley, and G. Yohe, Cambridge University Press, Cambridge, UK, 2006.

Alley, R., et al., *Climate Change 2007: The Physical Science Basis, Summary for Policymakers*, IPCC Secretariat, c/o WMO, 7bis, Avenue de la Paix, C.P. N ° 2300, 1211 Geneva 2, SWITZERLAND, 2007.

Bony, S., et al., How well do we understand and evaluate climate change processes?, *Journal of Climate*, *19*, 3445, 2006.

Forest, C. E., P. H. Stone, A. P. Sokolov, M. R. Allen, and M. D. Webster, Quantifying uncertainties in climate system properties with the use of recent climate observations, *Science*, *295*, 113, 2002.

Forest, C. E., P. H. Stone, and A. P. Sokolov, Estimated PDFs of climate system properties including natural and anthropogenic forcings, *Geophysical Research Letters*, *33*, L01,705, 2006.

Gregory, J. M., R. J. Stoufer, S. C. B. Raper, P. A. Stott, and N. A. Rayner, An observationally based estimate of the climate sensitivity, *Journal of Climate*, *15*(22), 2002.

Hansen, J., G. Russell, A. Lacis, I. Fung, D. Rind, and P. Stone, Climate reponse times: Dependence on climate sensitivity and ocean mixing, *Science*, *229*, 4716, 1985.

Hansen, J., et al., Forcings and chaos in interannual to decadal climate change, *Journal of Geophysical Research*, *102*, 25,679, 1997.

Hansen, J., et al., Target atmospheric $CO_2$: Where should humanity aim?, *The Open Atmospheric Science Journal*, *2*, 217–231, 2008.

Keller, K., B. M. Bolker, and D. F. Bradford, Uncertain climate thresholds and optimal economic growth, *Journal of Environmental Economics and Management*, *48*, 723, 2004.

Knutti, R., and G. C. Hegerl, The equilibrium sensitivity of the earth's temperature to radiation changes, *Nature Geoscience*, *1*, 735–743, 2008.

Knutti, R., T. F. Stocker, F. Joos, and G.-K. Plattner, Constraints on radiative forcing and future climate change from observations and climate model ensembles, *Nature*, *416*, 719–723, 2002.

Kriegler, E., Imprecise probability analysis for integrated assessment of climate change, Ph.D. thesis, University of Potsdam, 2005.

Levitus, S., J. Antonov, and T. Boyer, Warming of the world ocean, 1955–2003, *Geophysical Research Letters*, *32*, L02,604, 2005.

Meehl, G. A., et al., in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 747–845, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

Nordhaus, W. D., *A Question of Balance: Weighing the Options on Global Warming Policies*, Yale University Press, New Haven, CT, USA, 2008.

Roe, G. H., and M. B. Baker, Why is climate sensitivity so unpredictable?, *Science*, *318*, 629–632, 2007.

Royer, D. L., R. A. Berner, and J. Park, Climate sensitivity constrained by $CO_2$ concentrations over the past 420 million years, *Nature*, *446*, 530–532, 2007.

Tanaka, K., E. Kriegler, T. Bruckner, G. Hooss, W. Knorr, and T. Raddatz, Aggregated carbon cycle, atmospheric chemistry, and climate model (ACC2): Description of the forward and inverse modes, Reports on Earth System Science 40/2007, Max Planck Institute for Meteorology, Hamburg, 2007.

Tol, R. S. J., and A. F. de Vos, A Bayesian statistical analysis of the enhanced greenhouse effect, *Climatic Change*, *38*, 87, 1998.

Urban, N. M., and K. Keller, Probabilistic hindcasts and projections of the coupled climate, carbon cycle, and Atlantic meridional overturning circulation systems: A Bayesian fusion of century-scale observations with a simple model, submitted to *Tellus A*, 2008.

Weaver, A. J., et al., The UVic earth system climate model: Model description, climatology, and applications to past, present, and future climates, *Atmosphere-Ocean*, *39*, 361, 2001.

Weitzman, M., Structural uncertainty and the value of statistical life in the economics of catastrophic climate change, NBER Working Paper 13490, http://www.nber.org/papers/we13490, 2007.

Yohe, G. W., N. G. Andronova, and M. Schlesinger, To hedge or not against an uncertain climate future?, *Science*, *306*, 416, 2004.

Corresponding author: N. M. Urban, Department of Geosciences, Penn State, University Park, PA 16802, USA. (nurban@psu.edu)

K. Keller, Department of Geosciences, Penn State, University Park, PA 16802, USA. (klaus@psu.edu)